AD NUMBER
AD332699
CLASSIFICATION CHANGES
TO: **unclassified**
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LIMITATION CHANGES
TO: **Approved for public release, distribution unlimited**
FROM: **Controlling DoD Organization: Director, Naval Research Laboratory, Washington, DC 20375.**
AUTHORITY
NRL code/5309 memo dtd 20 Feb 1997; NRL Code/5309 memo dtd 20 Feb 1997

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AD NUMBER
AD332699
CLASSIFICATION CHANGES
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31 Oct 1974, per document marking, DoDD 5200.10

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DOD 5200.1-R, DEC 78

REVIEW ON 28 OCT 82

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NRL Report 584
Copy No. 89

A SYSTEM FOR THE EXTENSION OF UNAMBIGUOUS RADAR RANGE WITHOUT DEGRADATION OF VELOCITY INFORMATION

[UNCLASSIFIED TITLE]

J. R. Davis, J. M. Headrick,
and I. H. Page

Radar Techniques Branch
Radar Division

October 3, 1962

U. S. NAVAL RESEARCH LABORATORY
Washington, D.C.

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ABSTRACT
[Secret]

The present 455-nautical-mile unambiguous slant range of the Madre radar facility may be extended to 1365 nautical miles without the degradation of available doppler spread and range resolution which results from decreasing the pulse repetition rate. A cyclical stepping of the transmitted frequency spectrum, consisting of two sidebands symmetrically displaced about a common suppressed carrier, is used to preserve coherence of the velocity information conveyed by echoes of the three different frequencies.

PROBLEM STATUS

This is an interim report on one phase of the problem; work is continuing on this and other phases.

AUTHORIZATION

NRL Problem R02-17
Project RF 001-02-41-4006
AF-MIPR 30-635-8-160-6136
ARPA-160-60

Manuscript submitted September 10, 1962.

A SYSTEM FOR THE EXTENSION OF UNAMBIGUOUS RADAR RANGE WITHOUT DEGRADATION OF VELOCITY INFORMATION
[Unclassified Title]

INTRODUCTION

Most early efforts to improve the range-rate resolution of moving-target-indicating radar systems relied upon the use of extremely narrow filters to resolve doppler frequencies in real time. In order to cover all of the doppler frequencies of interest, at the ranges of importance to even conventional line-of-sight radars, a large number of such filters were necessary. Page (1) suggested a means of overcoming the difficulties associated with a large number of filters by utilizing a rotating magnetic drum upon which to store received information. This suggestion is based on the use of the pulse-doppler principle, in which samples of coherent echo pulses, stored on a rotating magnetic drum, are read sequentially off the drum and analyzed by a single scanning filter.

The Radar Techniques Branch of the Naval Research Laboratory, as a part of its long-term investigative program on radar signal processing methods, has developed a radar system employing the concepts embodied in Page's suggestion (2). The Madre radar was conceived as a long-range detection system whose original purpose was to explore the possibilities of early acquisition and tracking of fast-moving aircraft targets.

In order to be effective at ranges beyond the geometric horizon, Madre operates in the frequency band between 10 and 30 megacycles and utilizes ionospheric refraction to extend its range to over-the-horizon distances. A crosscorrelation technique, based on the pulse-doppler principle as mentioned above, helps to achieve the receiving-and-analysis system sensitivity necessary to exploit the low-amplitude echoes expected from targets beyond the horizon. In addition, rejection filters in the receiving system are matched to the usual backscatter returns, which otherwise would saturate the receivers and overwhelm the comparatively weak target returns.

It was postulated early in the development of the Madre system that such a radar would also be sensitive to echoes from launch-phase guided missiles of over-the-horizon origin, and so the problem of acquiring missile trajectory parameters with the intention of predicting impact points and/or intercept trajectories was included in the Madre program. It was also foreseen that the use of ionospheric refraction would make a high-frequency radar sensitive to ionospheric disturbances of the type generated by high-altitude nuclear explosions.

BACKGROUND

The existing Madre system utilizes a recording scheme which allows the impression of sampled echo pulses in 23 range intervals upon a magnetic drum, providing storage for information received during 20 seconds of receiver operation (3600 pulses at the designed 180 pps repetition rate). Drum storage is continuously modified by the replacement during each interpulse period of the oldest information stored upon it, and hence there is available a continuous display of 20 seconds of integrated echo amplitude. (In practice, the velocity-range presentation is renewed each two-and-one-half seconds.)

Operating at the design pulse repetition rate (180 pps) and with the 23-gate range storage implemented in the existent magnetic drum, the Madre radar provides a presentation of a maximum unambiguous range of 455 nautical miles and range resolution of 20 nautical miles. At its upper frequency limit, 26.6 Mc, the Madre system presents a maximum unambiguous radial target velocity of 1015 knots, and velocity resolution of 0.6 knots. At the Madre radar's lower limit in frequency, 13.0 Mc, the maximum unambiguous target velocity presented is increased to 2070 knots.

At an early stage in the development of the Madre system, it was suggested that an ionospheric radar could be built which would be capable of detecting aircraft targets at ranges of 1500 to 2000 nautical miles (2). The completion of a high-power transmitter (4.5-Mw peak power, 100-kw average power) and associated high-gain antenna array (26 db over an isotropic radiator at the 26.6-Mc upper frequency limit) for Madre in Autumn, 1961, provided the opportunity to make use of target echoes from extreme ranges, and aircraft have been tracked to date at distances as great as 1800 nautical miles (3). Missile launches from the Pacific Missile Range (PMR), approximately 2200 nautical miles from the Madre installation, also have been observed with some success (4) in spite of the necessity of using a lower gain antenna (16 db over an isotropic radiator) in the direction of PMR.

The use of the Madre research system to study targets at 2000-nautical-mile ranges presents an obvious range ambiguity problem: echo information from several 455-nautical mile intervals is superimposed upon the display. It is usually possible to ascertain the actual number and location of range intervals represented on the display by study of the backscatter ranges observed under a temporarily reduced repetition rate. Backscatter, however, typically extends over a span of more than the 455-nautical-mile unambiguous range and frequently extends into three range intervals. The existence of second-hop (and often third-hop) backscatter imposes an additional uncertainty upon the range origin of displayed information. Hence the Madre display generally presents superimposed target information from many range intervals. The range ambiguity may be significantly reduced by halving the pulse repetition rate (PRR) and doubling the pulse width, but with the attendant disadvantage that the available doppler spread is halved and the system thus becomes sensitive unambiguously to a maximum radial velocity of only 508 knots. Secondly, due to doubling the width of the transmitted pulse, the range resolution is seriously degraded.

An equally troublesome source of difficulty in the Madre research system is the presence on the display of returns from targets not actually beyond line-of-sight detection. Targets such as locally-operating aircraft and meteor ionization patches, frequently included in the information presented on the Madre display, contribute seriously to the confusion. In Fig. 1 is shown a series of photographs of the Madre display made during the launch phase of a Mercury-Atlas orbital flight from Cape Canaveral (AMR Test No. 1254, Sept. 9, 1961). Elapsed time after liftoff is indicated in seconds in the upper right corner of each frame. Velocity is presented on the vertical axis, and slant range appears on the horizontal axis. The computed missile slant-range and velocity, determined from postflight trajectory information, may be seen in frames (f) through (o) as a dotted cross in each frame.

As may be seen in all of the frames illustrated, the Madre display is continuously cluttered with an abundance of targets. The missile echo, which appears as an extensive smear in frames (i) through (m), actually makes its initial appearance in frame (g). In frames (g) and (h), however, the missile return is effectively obscured on the display by meteor echoes and local aircraft returns. Examples of the former (designated m) are most clearly evident in frames (f) and (i), and examples of the latter (designated a) in

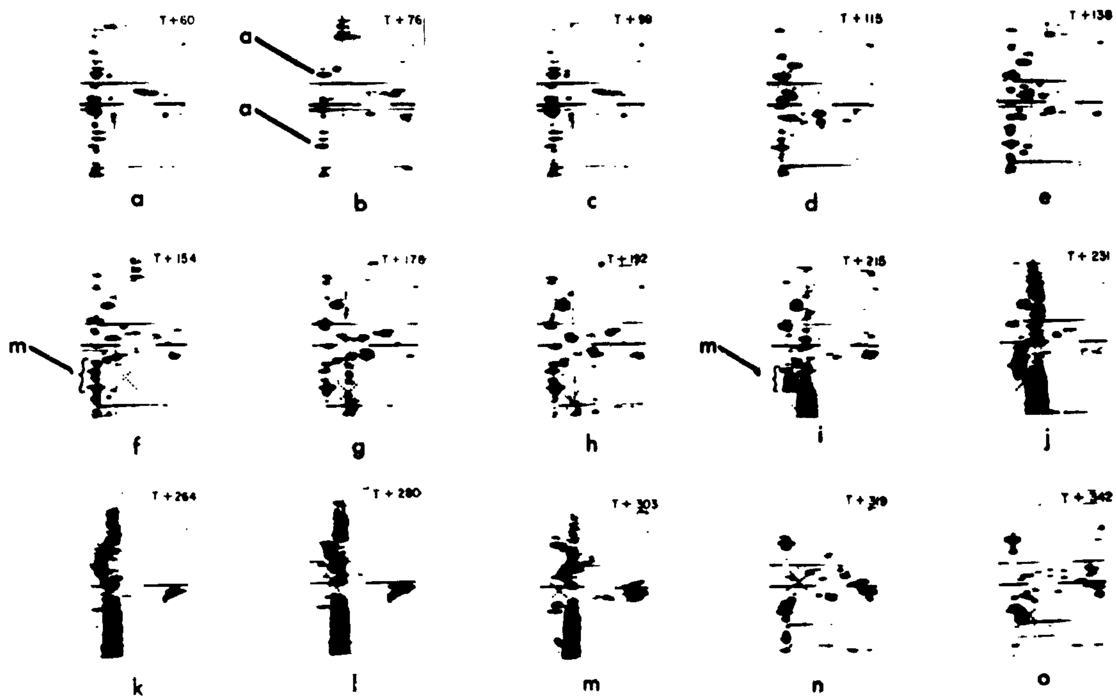


Fig. 1 - Series of Madre display photographs made during launch of Mercury-Atlas (AMR No. 1254, Sept. 9, 1961)

frame (b), persisting through frame (o). Due to a determination on the part of operating personnel not to permit an expected weak missile echo to escape detection, record, playback, and display levels were set to excessive sensitivity. Hence, the local aircraft targets illustrated are accompanied by their harmonics (similar vertically displaced traces), and the missile echo is of such strength as to saturate the magnetic drum, resulting in the large smear in frames (j) through (m) and an attendant disappearance of clutter.

A possible means of eliminating range ambiguity without the requirement of a reduction in PRR involves altering the transmitted frequency between pulses and sorting the echoes into separate receiving systems. A facility is provided with the original Madre research system to accomplish a cyclical, three-frequency stepping of transmitted frequency, thus extending the unambiguous range by a factor of three, to 1365 nautical miles. However, the frequency difference required to permit separation of the returns into three independent received channels imparts an incoherence to the doppler information carried by echoes of the three different frequencies. That is, the three echoes actually bear slightly different doppler shifts, due to the doppler frequencies' dependence upon their slightly different transmitted frequencies, and hence, when combined on the drum, the three echoes add as sine waves of different arguments. Because each of the three echoes actually carries doppler information which is independent of the other two returns, the facility merely furnishes data from three separate radar signals, each at one-third the PRR. The available unambiguous doppler spread, then, is effectively divided by three. Further, for a three-step cycle, the signal-to-noise ratio may be degraded by a factor of as much as three compared to the alternative choice of reducing the PRR by a factor of three.

In order to avoid the threefold loss in available doppler spread and the additional penalty in signal-to-noise ratio imposed by shifting among three different frequencies, a means is necessary to provide coherence between all of the transmitted pulses. A method for accomplishing the desired coherence-preserving frequency shift had been devised several years earlier, but it appeared infeasible to apply the scheme to moving target indication in the microwave radar systems of concern at the time, and hence the proposal was not developed fully. The method is to step in frequency, symmetrically about a common suppressed carrier, such that doppler information corresponding to the carrier itself may be derived from each pair of stepped sideband echoes. A more detailed development of the method may be found in Appendix A.

SYSTEM DESCRIPTION

A cyclical sequence of three symmetrically displaced sidebands, differing by 10 kc each, was chosen to implement the desired reduction in range ambiguity. The choice of three frequencies permits acquisition of unambiguous range information for a 1365-nautical-mile interval and, hence, provides for the typical spread of backscatter ranges. In addition, the display clutter due to near-range targets is repeated in the 1365- to 1820-nautical-mile interval, thus leaving uncluttered the 910-nautical-mile interval in which the Pacific Missile Range appears, and also the 2000-nautical-mile extreme of range at which it is expected that the range limit for detection of aircraft by the present Madre system is reached. Figure 2 illustrates the geographical coverage provided under normal ionospheric conditions by a multiple-receiver system utilizing a three-step sequence of transmitted frequencies. The shaded areas indicate cluttered regions whose target returns detected by the receiver, include echoes from local aircraft and meteor ionization patches. The two uncluttered regions are divided into two 455-nautical-mile intervals, each interval corresponding to the normal range-sensitivity interval of one of the remaining two separat receiving systems. The 10-kc frequency difference chosen between each of the three transmitted frequencies provides adequate separation for receiver discrimination of returned signals and yet does not impose rigorous bandwidth requirements upon receiver i-f stages.

Figures 3 and 6 illustrate the frequency-stepping exciter and receiver systems, respectively. In Fig. 3 it may be seen that all local oscillator frequencies, with the exception of the final variable-frequency oscillator (VFO) signal, are derived from a single 100-kc source. By using a common reference for all local oscillator frequencies, the coherence of the sidebands is preserved during operations in which they are processed separately. Crystal oscillators operating at frequencies of 510, 520, and 530 kc provide the sources from which the three double-sideband signals are derived. The stepping sequences are formed in three sequential modulators, each of which is provided with the three frequencies and a three-channel pulse sequence which gates the three frequencies in the proper order. Figure 4 is an illustration of this point. The PRR is used as a reference by the sequence generator, which forms a repetitive sequence of three gating pulses in separate channels. The three gating waveforms thus formed, along with the thre source signals, are provided to the sequential modulators, which construct the three different frequency sequences.

One of the three frequency sequences is fed to a pair of mixers, which creates the symmetrically displaced sidebands by combination with the 2.0 and 3.0-Mc references. Figure 5 illustrates this point.

*Provision for an alternate two-step or four-step cycle would permit coverage of the shaded areas in Fig. 2 when desired.

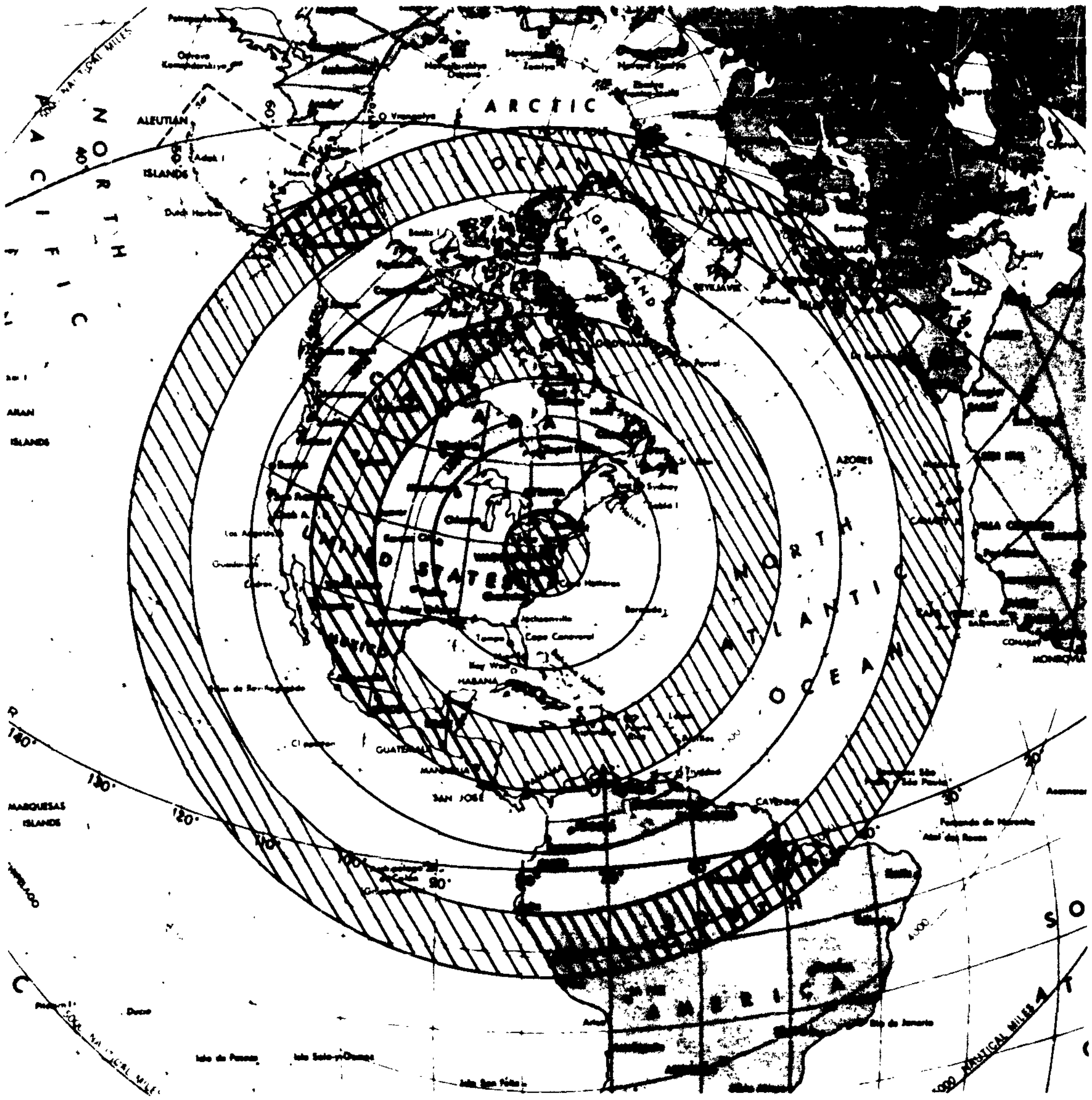


Fig. 2 - Azimuthal equidistant projection centered about Washington, D. C., showing (shaded) the regions in which targets are obscured on the frequency-stepped Madre display by returns from local aircraft and meteor ionization patches (made from U. S. Navy Hydrographic Office Chart No. 6705)

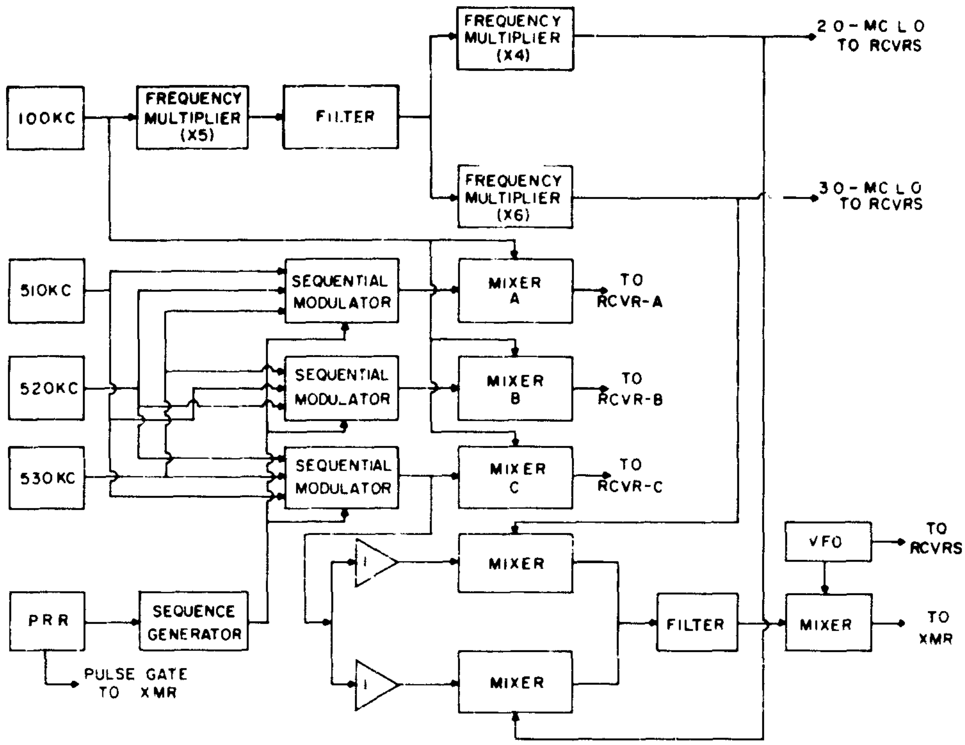


Fig. 3 - Block diagram of Madre frequency-stepped exciter system

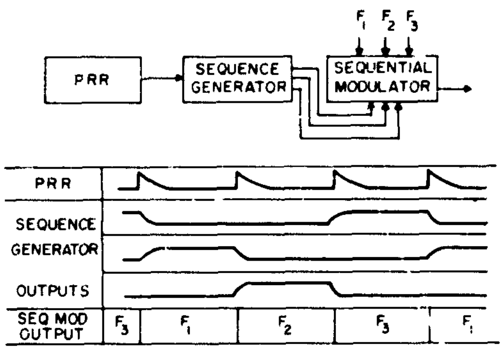
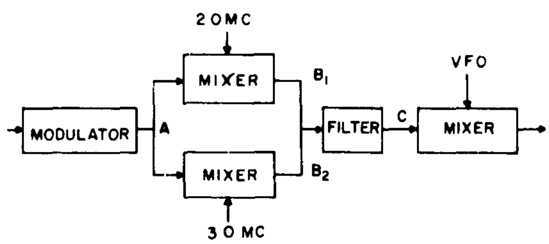


Fig. 4 - Operation of the sequential modulator as it accepts and properly sequences the three source frequencies for use in the Madre output

Fig. 5 - The mixing operation which converts one of the three different frequency sequences into the symmetrically displaced sidebands



If the output from one of the sequential modulators, point A in Fig. 5, is described by

$$(f_1, f_2, f_3) = (510 \text{ kc}, 520 \text{ kc}, 530 \text{ kc}),$$

then the mixer outputs are

$$\text{at } B_1: (2.510 \text{ Mc}, 2.520 \text{ Mc}, 2.530 \text{ Mc})$$

and

$$\text{at } B_2: (2.490 \text{ Mc}, 2.480 \text{ Mc}, 2.470 \text{ Mc})$$

accompained, in each expression, with the sidebands created in the pulsing process. The postmixing signal at C is

$$(2.5 \text{ Mc} \pm 10 \text{ kc}, 2.5 \text{ Mc} \pm 20 \text{ kc}, 2.5 \text{ Mc} \pm 30 \text{ kc})$$

which, after a final frequency translation, composes the desired sequence of symmetrically displaced sidebands about a common suppressed carrier.

All three sequential modulator outputs are provided (after a further frequency translation of 100 kc) to the three receivers, where they are subsequently utilized in a third receiver mixing process to translate the received signals to 100 kc, at which frequency level they may be introduced into the Madre analysis system. Each receiver thus provides information corresponding to a different 455-nautical-mile range. The output of mixer C in Fig. 3, being in the same sequence as the signal provided to the transmitter, will cause receiver C to furnish information from the first range interval. Mixer A, whose sequence is delayed by one pulse period from that fed to the transmitter, will cause receiver A to be sensitive to echoes received from the second range interval. Similarly, receiver B will yield information corresponding to targets within the third range interval.

The block diagram of a representative receiver is given in Fig. 6. The first two mixing operations are the exact inverse of the last two exciter mixing operations. The third mixing operation translates the sequential echo frequencies to the 100-kc level necessary for use in the Madre research analysis system.

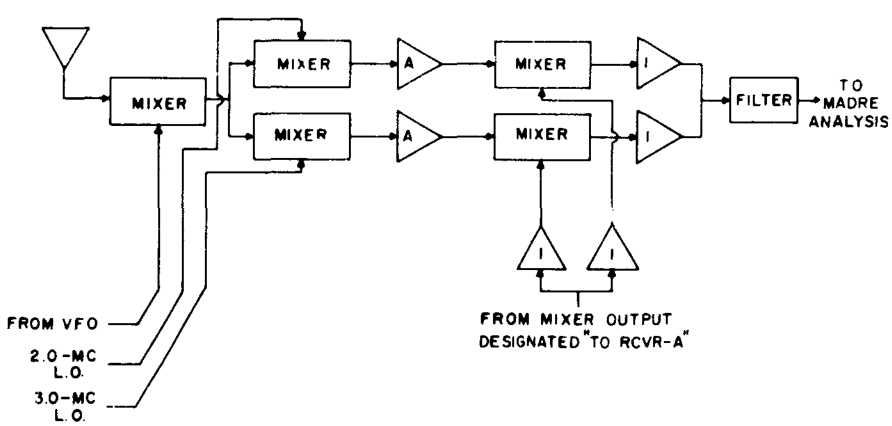


Fig. 6 - Block diagram of Madre frequency-stepped receiver system

SYSTEM STATUS

At the present time, the design, construction, and initial testing of the individual components has been completed. Evaluation of the entire system is awaiting the procurement of a filter (now on order from a commercial concern) necessary to achieve the desired sideband structure described in Appendix A.

A proposal has been investigated to replace the fixed 10-kc frequency-step provision with a method of generating random frequency shifts between pulses. Such a modification is necessary in view of the extremely crowded condition of the hf band. It is expected that a means of shifting among randomly selected frequencies over a wide range will greatly reduce the effects of interference on Madre's efficiency. Random frequency stepping, of course, will enhance the system's performance against countermeasures. A system utilizing random frequency shifts is presently in the initial stages of development.

ACKNOWLEDGMENT

The authors gratefully acknowledge the assistance of the Radar Techniques Branch and, in particular, Mr. F. H. Utley and Mr. W. C. Headrick who contributed generously of their time and knowledge. The work performed on this problem was funded by the Advanced Research Projects Agency (ARPA Order No. 160-61, Amendment No. 1 of 9 Nov. 1961) and, to a certain extent, by the United States Air Force.

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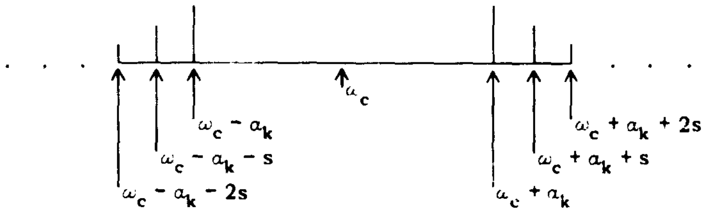
APPENDIX A

DISCUSSION OF FREQUENCY STEPPING

Consider a transmitted signal consisting of a pair of sidebands separated in frequency from a suppressed carrier ω_c by α_k and filtered to possess the spectral structure indicated below:



s represents the angular equivalent of the PRR. If each sideband is itself a single-sideband-type signal, as shown, the redundancy inherent in the transmission of two double-sideband signals will be avoided. The total transmitted signal may then be expressed as

$$\sum_0^j A_i \cos(\omega_c + is + \alpha_k)t + \sum_0^j A_i' \cos(\omega_c - is - \alpha_k)t,$$

where i, running from 0 to j, indicates the harmonics engendered in the pulsing process.

After reflection from an approaching target moving with velocity v, the (now doppler-shifted) signal received is

$$\sum_0^j B_i A_i \cos\left[\omega_c + is + \alpha_k + \frac{2v}{c}(\omega_c + is + \alpha_k)\right]t$$

$$+\sum_0^j B_i' A_i' \cos\left[\omega_c - is - \alpha_k + \frac{2v}{c}(\omega_c - is - \alpha_k)\right]t.$$

Each of the two signals is processed in a separate receiver channel, and through appropriate i-f action $\omega_c + \alpha_k$ may be removed from the upper sideband and $\omega_c - \alpha_k$ may be removed from the lower sideband, leaving

$$\sum_0^j B_i A_i \cos\left[is + \frac{2v}{c}(\omega_c + is + \alpha_k)\right]t$$

$$+\sum_0^j B_i' A_i' \cos\left[-is + \frac{2v}{c}(\omega_c - is - \alpha_k)\right]t.$$

The frequency components due to the pulsing operation may be removed by the rejection filters mentioned in the Introduction to this report, and the resultant signal is

$$\sum_{0}^{j} B_i A_i \cos \frac{2v}{c} (\omega_c + is + \alpha_k)t$$

$$+ \sum_{0}^{j} B_i' A_i' \cos \frac{2v}{c} (\omega_c - is - \alpha_k)t,$$

which may be combined in a product detector to yield

$$\sum_{-j}^{j} \left\{ C_i \cos 2\left(\frac{2v}{c} \omega_c t\right) + D_i \cos 2\left[\frac{2v}{c} (is + \alpha_k)\right]t \right\},$$

the second term of which may easily be eliminated by passing the signal through a high-pass filter; the remainder

$$C \cos 2\left(\frac{2v}{c} \omega_c\right)t$$

is the desired true function of the doppler frequency imposed upon the carrier at reflection from the target.

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MEMORANDUM

20 February 1997

Subj: Document Declassification

Ref: (1) Code 5309 Memorandum of 29 Jan. 1997
(2) Distribution Statements for Technical Publications NRL/PU/5230-95-293

Encl: (a) Code 5309 Memorandum of 29 Jan. 1997
(b) List of old Code 5320 Reports
(c) List of old Code 5320 Memorandum Reports

1. In Enclosure (a) it was recommended that the following reports be declassified, four reports have been added to the original list:

Formal: 5589, 5811, **5824**, 5825, 5849, 5862, 5875, 5881, 5903, 5962, 6015, 6079, 6148, 6198, 6272, 6371, 6476, 6479, 6485, 6507, 6508, 6568, 6590, 6611, 6731, 6866, 7044, 7051, 7059, 7350, 7428, 7500, 7638, 7655. Add **7684**, **7692**.

Memo: 1251, 1287, 1316, **1422**, [redacted], 1500, 1527, 1537, 1540, 1567, 1637, **1647**, **1727**, **1758**, 1787, 1789, 1790, 1811, 1817, 1823, **1885**, 1939, **1981**, 2135, 2624, 2701, 2645, 2721, 2722, 2723, 2766. Add **2265**, **2715**.

The recommended distribution statement for the these reports is: **Approved for public release; distribution is unlimited.**

2. The above reports are included in the listings of enclosures (b) and (c) and were selected because of familiarity with the contents. The rest of these documents very likely should receive the same treatment.

J. M. Headrick
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